



WATER RESOURCES RESEARCH GRANT PROPOSAL

Title: Records of Holocene Climatic and Hydrologic Variability in Spring Tufa From Kentucky: Will Global Climate Changes Affect Water Availability in Karst Terrains of the Mid-Continent Area?

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Critical Regional Water Problem Being Addressed

With time, an increasing proportion of the total surface and subsurface water runoff is being withdrawn to satisfy the growing needs of our society (Domenico and Schwartz, 1990). In the United States, approximately every fifth molecule of water participating in runoff is being already withdrawn to supply the existing demand. As an ever-larger portion of the hydrologic system is being utilized, our society becomes increasingly vulnerable to the natural variability in the amount of runoff. In this situation, adverse climatic conditions, e.g., prolonged droughts, may easily limit water availability. This trend is especially worrisome given the scientific concerns about impeding global climate changes that may significantly alter the global and regional climatic patterns in the next several decades (Keeling et al., 1995). Global climate simulations indicate that one of the possible effects of the ongoing global warming may be increased variability of climate causing more frequent extreme droughts or high-rainfall conditions (Conway, 1998).

More than 50% of Kentucky and 20% of the United States is underlain by karst aquifers. There are several hydrogeologic and socio-economic reasons why the expansive karst terrains in Kentucky and the neighboring states may be especially vulnerable to at least local, drought-induced water shortages. Groundwater drainage in these mature karst terrains takes place predominantly through networks of interconnected cavities that allow water flow at rates that are typically orders of magnitude faster than groundwater flow rates in porous aquifers (Quinlan and Ewers, 1981). Thus, residence time of groundwater in these aquifers is relatively short and that makes them especially vulnerable to variations in recharge, e.g., droughts. In addition, the considered karst terrains are occupied mainly by dispersed, rural population whose water supply comes largely from karst springs or wells tapping shallow karst (e.g., Edwards, 1998). Development of reliable, central water supply systems is inherently expensive in communities with a sparsely distributed population. For rural, largely agricultural communities high cost may be a significant impediment. It is thus of paramount importance to assess the potential for significant future, global-warming-related variability of recharge in these karst terrains. Such information is needed for proper water management policies over the next several decades when combined effects of growth in water demand and global warming may put a new level of stress on the existing water resources in the mid-continent area.

Expected Results and Benefits

When considering the possible future effects of global warming on regional climatic and hydrologic conditions, it is important to remember that only several thousand years ago global climate was also a few degrees Centigrade warmer than today (Ciais et al., 1992). This so-called "Holocene climatic optimum" may tell us what to expect if our planet warms up by a few degrees in the next several decades. Karst terrains are very promising for paleoclimatic and paleohydrologic studies of the climatic optimum because they frequently contain secondary calcite deposits, e.g., cave speleothems or spring tufas (White, 1976). These deposits can be reliably dated using the U-Th disequilibrium technique and can be chemically analyzed in search of proxies of specific past climatic and hydrologic conditions.

In the proposed study, I will use spring tufa from Three Hundred Springs in the area of Cave City, Kentucky, to search for chemical proxies of past drought conditions during the colder part of the Holocene (ca. 0 - 5,000 years B.P.) and during the warm Holocene climatic optimum (ca. 5,000 - 8,000 years B.P.). Based on previous studies in other areas, such chemical proxies of droughts are generated by an increase in evapotranspiration. These proxies may include: (1) increase in the relative abundance of heavy oxygen and hydrogen isotopes, ^{18}O and ^2H , in calcite and in water inclusions, and (2) increase in the abundance of major and trace elements in calcite (e.g., Mg, Sr). By combining U-Th dating with UV microscopy, I expect to tie the drought proxy record to a chronology that may achieve time resolution of the order of one year. The resulting data will demonstrate whether during the warmer part of Holocene the study area has experienced droughts more frequently than during the later, colder part of Holocene. Based on the collected data, I will construct simple geochemical models to make quantitative predictions of the potential influence of global warming on drought frequency and groundwater recharge in

this part of Kentucky. The data and models obtained in this study may be ultimately used as a scientific basis for making decisions regarding the future management of water resources in karst terrains of Kentucky and the neighboring states.

Nature, Scope, and Objectives of Research

Previous studies have shown that isotopic and chemical composition of secondary calcite deposits (e.g., speleothems and spring tufa) is sensitive to variations in climatic and environmental conditions that occurred at the time of calcite precipitation (e.g., surface temperature, residence time of water in the epikarstic zone and in the aquifer, intensity of evapotranspiration (Bar-Matthews et al., 1996; Drake, 1980; Drake and Wigley, 1975; Gascoyne, 1983; Ivanovich and Harmon, 1992; Lauritzen et al., 1986; Yonge et al., 1985). Different chemical elements released into the water infiltrating through soils into karst aquifers become subsequently trapped in the layers of precipitated calcite. In this study, I will test the hypothesis that future global warming may be associated with increased occurrence of droughts. This test will be performed using geochemical evidence for past droughts that may exist in secondary calcite deposits from south-central Kentucky. The underlying assumption is that the warm "Holocene climatic optimum" may be used as an analog of the future global warming (Conway, 1998). Scientifically, this study has three interrelated objectives:

- to construct a detailed Holocene chronology of the secondary calcite deposits,
- to obtain a record of variations in elemental and stable isotope composition of the Holocene calcite, and
- to derive quantitative estimates of the possible variations in drought frequency and severity during the Holocene climatic optimum.

The proposed geochemical record will be obtained from tufa of Three Hundred Springs, a secondary calcite deposit located on the banks of the Green River in the mature karst terrain of the Pennyroyal Plain near Cave City, Kentucky (Figures 1 and 2). This location has been selected after preliminary field investigations during three field excursions in the period September through November 1998. My field observations and review of the relevant literature (e.g., Hess et al., 1989; Hess and White, 1989; Jillson, 1957; Miotke and Palmer, 1972; Palmer, 1981; Pohle et al., 1964; Quinlan and Ewers, 1981) have yielded several reasons supporting the choice of this site:

- calcite depositions is still taking place there at present and the geologic record that will be derived from the tufa is likely to cover the period of interest (Holocene);
- the isotopic and chemical composition of the tufa should reflect predominantly paleoclimatic changes (e.g., droughts) because this calcite deposit is located at the end of a small, local groundwater basin that should have no significant internal dynamics which could overprint the climatic record;

- the tufa at Three Hundred Springs has thickness of several meters and relatively high calcite deposition rates (Jillson, 1957) with both factors promising a high-resolution Holocene record; and
- owners of the property on which the tufa is located have already expressed permission for sample collection.

Tufa deposits are used less frequently than speleothems in geochemical investigations of paleoclimates and paleoenvironments. However, my preliminary inspection of the Three Hundred Springs tufa has shown that this deposit shares many crucial morphologic and petrographic features of speleothems. For instance, many broken off pieces of the tufa had shown internal macroscopic banding that is so characteristic of speleothem calcite. The Three Hundred Springs deposit includes also features that are similar to cave stalgmities, stalactites and draperies. Based on these similarities, I believe that the mechanisms of calcite deposition in the Three Hundred Springs tufa is analogous to the mechanism that generates typical speleothems, which have been previously proven to contain paleoclimatic and paleoenvironmental records.

In the case of secondary calcite deposits, detailed chronology with temporal resolution approaching annual can be obtained by combining the Thermal Ionisation Mass Spectrometry (TIMS) U-Th disequilibrium dating with UV-microscopic counting of calcite micro-banding (Baker et al., 1996, 1998; Edwards et al., 1987; Kaufmann et al., 1998). Older, less precise technique of U-Th dating has been successfully used on speleothems from Kentucky (Mammoth Cave) (Harmon et al., 1978; Hess and Harmon, 1981). The UV-luminescent micro-banding is due to variations in the organic acid content of calcite with time (Lauritzen et al., 1986) and has been used in a number of different studies as a basis for a high-resolution chronology (Baker et al., 1996, 1998; Popov et al., 1994). The UV-microscopy will be performed together with regular optical microscopy on thin sections covering all of the calcite samples that will be determined with U-Th dating to fall within the Holocene period.

In the second stage of this study, chemical and isotopic composition of dated calcite samples will be analyzed to derive the proxy record of past droughts. The main focus of the elemental analyses will be on obtaining high-resolution record of two important major elements, Mg and Sr. This pair of elements is important because in the case of Mg its incorporation into precipitating calcite is temperature-dependent but incorporation of Sr is not (Gascoyne, 1983). Any positive covariance in Mg and Sr concentration must then be due to factors other than ambient temperature at the time of precipitation, e.g., due to positive correlation of these two elements in the karst waters from which the calcite precipitates. Such positive correlation is likely to be caused by changes in the relative importance of evapotranspiration (e.g., Bar-Matthews et al., 1996) that should, in turn, reflect drought frequency and severity which is of interest in this study.

A high-resolution record of Mg and Sr abundance in the calcite samples will be obtained using an electron microprobe.

As an independent check of my interpretation that any positive covariance of Mg and Sr concentration is due to changes in evapotranspiration, I will also obtain a multi-elemental composition data as well as oxygen and hydrogen stable isotope data for forty selected calcite subsamples. These subsamples will be selected based on my examination of the Mg and Sr record with a special attention being paid to these parts of the calcite cores that will have contrasting concentrations of these two elements. The analytical procedures employed at this stage will be stable isotope mass spectroscopy plus major and trace element analysis in an ICP-MS. The ICP-MS elemental data will be compared to the Mg, Sr data from the electron microprobe for the same parts of the core. I will assume that the evapotranspiration/drought signal will be expressed by positive covariance of all the analyzed elements because the trade off between infiltration and evapotranspiration should express itself as a trade off between dilution and concentration of ions in karst groundwaters from which the analyzed spring tufa precipitated. Similarly, the influence of evapotranspiration on oxygen and hydrogen isotopic ratios should be very pronounced because these isotopes fractionate during evapotranspiration leading to enrichment of heavy isotopes in the remaining groundwater (Bar-Matthews, 1996). Based on these chemical reasons, I expect that combination of the isotopic and elemental data will permit me to extract a reliable proxy record of past drought frequency and severity.

Interpretation of the collected data will be done in a framework of simple geochemical modeling aimed at providing quantitative estimates of drought frequency and severity. In the case of the elemental data, I will extract the trends of positive covariance amongst the various elements using the Principal Component Analysis (Rollinson, 1993) and will interpret this covariance in the context of a simple linear mixing model in which concentration of all elements is being changed by evapotranspiration. For the purpose of quantitative interpretation of the isotopic data, I will develop a fractionation model based on the assumption that evapotranspiration is the main process controlling water mass balance and the isotopic composition of water in the considered karst system. Results of my modeling will be used to estimate quantities of runoff and evapotranspiration under "warm" and "cold" Holocene conditions as compared to today's runoff and evapotranspiration of which each accounts for approximately half of the modern precipitation in the study area (Hess et al., 1989).

Having the dated record of elemental and oxygen/hydrogen isotopic variations over the last several thousand years, I will be able to answer the question whether the warm "Holocene climatic optimum" was characterized by more frequent droughts than the current, colder Holocene climate. These results can be used as an indication of the changes in the quantity of water that will be recharging the karst aquifers in Kentucky under future conditions of global warming.